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## Effects of temperature, soil water status, and soil type on swine slurry nitrogen transformations

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**Abstract** Manure N dynamics are affected by manure characteristics, soil factors, and environmental conditions. An incubation experiment was conducted to assess the relationship of these factors. The effects of temperature (11, 18, and 25°C), soil texture (three soils, silt loam to sandy loam), and soil water status (constant at 60% water filled pore space, WFPS, and fluctuating between 30% and 60% WFPS) on net mineralization and nitrification of swine manure N were assessed. Swine manure was applied at an equivalent rate of 350 kg total N ha<sup>-1</sup> to 250 g air-dry soil in 2-l canning jars. Subsamples were taken from each jar for NO<sub>3</sub><sup>-</sup> and NH<sub>4</sub><sup>+</sup> determination when fluctuating moisture treatment dried to 30% WFPS, with sampling continuing through four wet-dry cycles at each temperature. Manure NH<sub>4</sub><sup>+</sup> was rapidly nitrified to NO<sub>3</sub><sup>-</sup>. The relationship between NO<sub>3</sub><sup>-</sup> accumulation and degree days after application (DDAA, 0°C base) could be described across temperatures using a single pool exponential model for each soil. More NO<sub>3</sub><sup>-</sup> accumulated in coarser-textured soils (150–200 mg N kg<sup>-1</sup> soil), compared to 130 mg N kg<sup>-1</sup> soil in the silt loam soil. Fluctuating soil water status did not alter estimates of rate and extent of NO<sub>3</sub><sup>-</sup> accumulation, but slowed NH<sub>4</sub><sup>+</sup> disappearance somewhat.

**Keywords** Nitrogen · Mineralization · Nitrification · Manure slurry

### Introduction

Transformations of N applied from manure or other organic amendments are affected by numerous biotic and

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abiotic factor. It is important to account for the individual and interactive effects of these factors in developing estimates of plant available N (PAN) from manures. Characteristics of the manure amendment clearly have a large impact on the availability of N. Castellanos and Pratt (1981) demonstrated large differences in the mineralization of manure organic N from different ruminant and monogastric livestock species. In general, the availability of N, measured as the accumulation of mineral N during a period of aerobic incubation, increased as manure N concentration increased. Gordillo and Cabrera (1997a) showed that within an animal species (e.g. poultry) the availability of N was influenced by manure characteristics, including uric acid and total N concentration.

After application to soil, the transformations of N from a specific manure or slurry are controlled largely by three factors: temperature, soil water status, and soil type or texture. Hadas et al. (1983) showed that the accumulation of NH<sub>4</sub><sup>+</sup> during the early stages of an aerobic incubation, indicative of organic N mineralization, increased with incubation temperature. Stark (1996) provided estimates of nitrification rate over a broad range of temperatures (5–50°C), with maximal rates occurring in the range 30–35°C. Grundmann et al. (1995) conducted a similar assessment, but found optimal temperatures to be 20–25°C. Under high soil water conditions, formation of N<sub>2</sub>O and loss of N via denitrification also increase with temperature (Maag and Vinther 1999). Griffin and Honeycutt (2000) showed that when soil water content was near-optimal, consumption of NH<sub>4</sub><sup>+</sup> and accumulation of NO<sub>3</sub><sup>-</sup> (i.e. net nitrification reaction) from different manures at temperatures of 10–24°C could effectively be modeled using degree days after application (DDAA) to account for differences in temperature.

The impact of soil water on N transformations is varied and in many cases has been related to the experimental procedures employed. Numerous incubation experiments have held soil water content constant at different levels. Stanford and Epstein (1974) provide an example of this approach, and concluded that soil N mineralization was a

linear function of soil water content when between 0.33 and 15 bars, although there was a clear interaction with soil type. Flowers and O'Callaghan (1983) demonstrated that nitrification of swine slurry N in soil was affected by soil water content, with optimal levels of around 60% of soil water holding capacity (WHC). When soil water content is high, e.g. 70–100% water-filled pore space (WFPS), denitrification reactions are favored as demonstrated clearly by Linn and Doran (1984) and Weir et al. (1993). The effects of fluctuating soil water content have been more difficult to assess. In general, drying soil *to air-dry status*, followed by rewetting, commonly causes a flush of N (and C) mineralization. This was shown by Birch (1964) and Cabrera (1993), and can be attributed to the biocidal effects of desiccation on soil microorganisms. Fluctuation of soil water within narrower ranges, as might be expected in humid climates under field conditions, has not been assessed.

Variations in soil texture that result in differences in soil water content or aeration may confound attempts to estimate the rate and extent of N transformations as influenced by texture. Under conditions that are near-optimal for mineralization and nitrification (20–30°C, soil water content 50–65% WFPS), textural differences influence the availability of applied manure N. Gordillo and Cabrera (1997b) applied the same broiler litter to nine soils, and measured net N mineralization over 146 days. Both the rate and extent of mineralization of manure organic N showed a strong positive correlation with sand content of the soil, and a strong negative correlation with silt + clay content. Thomsen and Olesen (2000) also found that increased sand content generally led to increased C mineralization from manures, presumably due to both increased aeration in sandy soils and increased physical protection of C and N substrates as the soil clay content increased.

Previously, we demonstrated that the effects of temperature on net nitrification from manures could be predicted under optimal aeration based on DDAA (Griffin and Honeycutt 2000). In the research reported here, we extend this approach in evaluating N transformations following application of swine slurry. Our objective was to evaluate the individual and interactive effects of temperature, soil water status over time, and soil texture on slurry N transformations.

## Materials and methods

### Soil and manure materials

The soils used for this laboratory experiment were collected from the USDA-ARS research sites at Newport (loam, no established soil series designation; coarse-loamy, mixed, frigid, Typic Haplorthod) and Presque Isle (Caribou sandy loam, fine-loamy, mixed, frigid, Typic Haplorthod), Maine, United States, and from the University of Illinois at Champaign-Urbana (Catlin silt loam, fine-silty, mixed, superactive, mesic, Oxyaquic Arguidoll), Illinois, United States. These soils will be referred to as Newport, Caribou, and Catlin, respectively. The particle size distribution and initial

**Table 1** Selected properties of Caribou, Newport, and Catlin soils used in aerobic incubation experiment

	Caribou	Catlin	Newport
Sand (%)	51	14	42
Silt (%)	41	67	52
Clay (%)	8	19	6
pH	5.7	7.0	5.9
CEC	7.3	20.1	4.6
P (kg ha <sup>-1</sup> )	14	21	7
K (kg ha <sup>-1</sup> )	244	639	321
Total C (%)	2.19	2.86	2.52

nutrient content are shown in Table 1. Particle size distribution was estimated using the rapid sieving procedure of Kettler et al. (2001), following dispersion of 5 g dry soil in 30 ml 3% hexametaphosphate (HMP). At each site, soil was collected from the Ap horizon (0–20 cm), air-dried, sieved (2 mm), and stored at 4°C until experiments were initiated. Soil nutrient concentration was determined using modified-Morgan extraction (2 g dry soil in 10 ml pH 4.8, 0.62 M NH<sub>4</sub>OH + 1.25 M CH<sub>3</sub>COOH, shaken for 15 min.) and inductively coupled plasma emission spectroscopy (ICP). Swine slurry manure was collected at the USDA-ARS facility at Clay Center, Nebraska, United States. This slurry contained 3.6% dry matter (DM), 0.49% total N, and 0.36% NH<sub>4</sub><sup>+</sup>-N (i.e. 78% of total N). Total N was measured by Kjeldahl digestion, and manure P and K concentration (0.11% and 0.27%, respectively) were measured by dry combustion, followed by digestion in 0.5 M H<sub>2</sub>SO<sub>4</sub> and ICP.

### Aerobic incubation methodology

The soils described above were used in an aerobic incubation experiment similar to that of Griffin and Honeycutt (2000). This incubation evaluates the effects of *soil type* (three soils, as in Table 1), *soil water status* (constant at 60% WFPS vs fluctuating between 30% and 60% WFPS) and *temperature* (11, 18, and 25°C) on net mineralization and nitrification after the application of liquid swine manure. In 2-l canning jars, 250 g soil (oven-dry equivalent) was gently packed to a density of 1.2 Mg m<sup>-3</sup>. Sufficient deionized water was added to wet the soil to 45% WFPS (gravimetric water content of 25%). Fifty-four jars were prepared for each soil. At each of the three temperatures, jars were preincubated for 7 days. After the preincubation period, the slurry treatment was applied and the two moisture regimes were initiated. Swine slurry sufficient to supply 200 mg total N kg<sup>-1</sup> dry soil (equivalent to 350 kg N ha<sup>-1</sup>, 78% as NH<sub>4</sub><sup>+</sup>-N) was applied to the surface of half of the jars, and was then thoroughly stirred into the soil within 5 min of application, to minimize volatile N loss. The unamended control soil was stirred in the same way. All soils were again packed to density of 1.2 Mg m<sup>-3</sup>, and deionized water was applied as a mist until soil water content reached 60% WFPS. Triplicate jars of each soil/amendment/moisture combination were then placed in constant temperature incubators at 11, 18, and 25°C. Individual jars were incubated at the same temperature as their preincubation period. Jars that were to remain at constant soil water content (60% WFPS) were loosely capped with metal canning-jar lids. These jars were aerated for 1 h each day, by removing the lid, and were then weighed; deionized water was misted onto the soil surface to replace evaporative loss. The remaining jars, subjected to slow drying to 30% WFPS, had the same lids except that each lid had two holes (1.25 cm diameter) drilled through it. This allowed water loss to occur slowly (shown below). These jars were also weighed daily, to identify when they reached the target soil water level.

Soil was sampled immediately after the slurry was applied, and each treatment (soil type/temperature combinations) was subsequently sampled at the end of four drying cycles. When the variable soil water treatment reached 30% WFPS, the soil was rewet to 60%

WFPS and both the variable and constant soil water jars were immediately sampled as a set. This means that the interval between sampling for each set of jars was not constant. Approximately 10 g soil (oven-dry basis) was removed from each jar, using a 1.4-cm-diameter cork borer. Inorganic N ( $N_i$ ;  $NO_3^-$ -N +  $NO_2^-$ -N and  $NH_4^+$ -N) was determined colorimetrically on a Lachat Autoanalyzer (Lachat Instruments, Mequon, Wis.) following extraction of 5.0 g soil in 50 ml 2 M KCl for 1 h, on a wrist-action shaker. Gravimetric soil water was determined by drying 5.0 g soil at 105°C, for 24 h.

We assessed net N transformations over DDAA to standardize across temperature treatments. Cumulative nitrification ( $N_{cum}$ ) for manure-amended soil, measured as soil  $NO_3^-$ -N concentration at time,  $t$ , corrected for nitrification in the unamended soil and for initial soil  $NO_3^-$  content, was calculated as in Griffin and Honeycutt (2000) and Sims (1986):

$$N_{cum}(\text{mg kg}^{-1} \text{ soil}) = (NO_3^- - N)_{\text{manure}} - (NO_3^- - N)_{\text{control}} - (NO_3^- - N)_{t=0} \quad (1)$$

Soil concentration of manure-derived  $NH_4^+$  at time,  $t$ , was defined similarly as:

$$N_{amm}(\text{mg kg}^{-1} \text{ soil}) = (NH_4 - N)_{\text{manure}} - (NH_4 - N)_{\text{control}} - (NH_4 - N)_{t=0} \quad (2)$$

Cumulative nitrification was fitted to a single pool exponential model, as used by Deans et al. (1986), to estimate nitrified N ( $N_{cum}$ ) and the associated rate constant,  $k$ , over thermal time:

$$N_{cum} = N_0(1 - e^{-k \times DDAA}) \quad (3)$$

The consumption of manure  $NH_4^+$  was fitted using a linear model, as:

$$N_{amm} = N_A + b \times DDAA \quad (4)$$

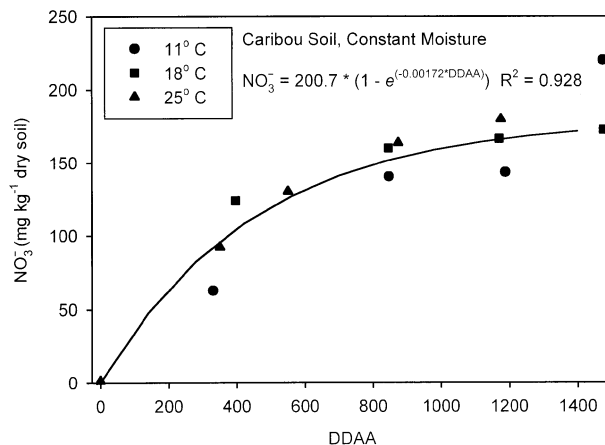
where  $N_A$  is the concentration at  $t=0$ . Equations were fitted using all data points, although only mean values (of three observations each) are shown in the figures. Equations were calculated using nonlinear curve fitting via a Marquardt iteration (SYSTAT, Version 10.0; SPSS, Chicago, Ill.). Regression equations were deemed significantly different if the 95% confidence intervals around the parameters (the rate constant,  $k$ , for example) did not overlap.

## Results and discussion

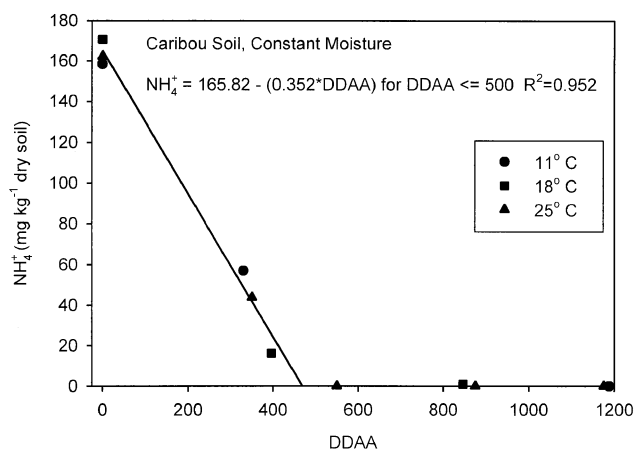
### Predicting N transformations using DDAA

Conditions in this aerobic incubation, under constant soil water, were expected to be optimal for mineralization and nitrification, minimizing gaseous N losses due to either  $NH_3$  volatilization or denitrification. If so, then we should be able to standardize the effects of incubation temperature by using "thermal time" or DDAA, rather than days after incorporation of the slurry, as had been done initially by Honeycutt et al. (1988) and was later applied to manure N by Griffin and Honeycutt (2000). Figure 1, using the Caribou soil at constant soil water, provides an example of the effectiveness of this DDAA approach. The accumulation of  $NO_3^-$ , an estimate of net nitrification, is easily fitted to the single pool (two-parameter) exponential model using data from the three incubation temperatures, even though the length of the incubation varied from 55 days (at 25°C) to 135 days (at 11°C). The estimate of  $N_{cum}$  (200.7 mg N kg<sup>-1</sup> soil) indicates that, under these conditions, all of the N applied in the slurry would be nitrified by 1,500 DDAA.

The consumption of  $NH_4^+$  is a linear function of DDAA (Fig. 2). All of the applied  $NH_4^+$  was recovered at  $t=0$ , and as nitrification of this N (plus any N mineralized from the manure organic N fraction) proceeds very quickly, was nitrified by 470 DDAA. This is slightly higher than the 340 DDAA estimate that we developed



**Fig. 1** Accumulation of nitrate-N ( $NO_3^-$ ) in Caribou sandy loam soil following application of swine slurry, as a function of degree days after application (DDAA; 0°C base). Data points are means of three observations



**Fig. 2** Consumption of ammonium-N ( $NH_4^+$ ) in Caribou sandy loam soil following application of swine slurry, as a function of degree days after application (DDAA; 0°C base). Data points are means of three observations

earlier for  $NH_4^+$  applied in liquid dairy manure, solid poultry manure, or swine manure (Griffin and Honeycutt 2000).

### Effects of soil water regime on slurry N transformation

Nitrate accumulation in each of the six combinations of soil type and soil water was successfully fitted using the single-pool exponential model; this model accounted for 65–95% of the variation in  $NO_3^-$  concentration. The estimates of  $N_{cum}$  and  $k$  parameters are shown in Table 2 for each combination. Even though the three soils differed in texture, they dried at similar rates. The rate of drying (average of three soils) is shown in Fig. 3, using the first drying cycle as an example. The amount of time needed to reach 30% WFPS decreased as incubation temperature increased, but drying rate was not a direct function of DDAA, probably due to differences in relative humidity between incubation chambers maintained at different temperatures. Drying rate was also not affected by the application of the swine slurry (data not shown), which represented a relatively small organic matter input.

Within each soil type, there were no significant differences in the parameter estimates for constant versus fluctuating soil water

**Table 2** Estimates of cumulative nitrified N ( $N_{cum}$ ) and rate of nitrification ( $k$ ), using a single-pool exponential model [ $N_{cum} = N_0(1 - e^{-k \times DDAA})$ ], for constant and fluctuating soil water regimes on Caribou, Catlin and Newport soils

Soil	Soil water	$N_{cum}^a$ mg $NO_3^-$ kg $^{-1}$ soil	$k^a$ DDAA $^{-1}$	$R^2$
Caribou	Constant	200.7a	0.00172c	0.93
	Fluctuating	194.8a	0.00176c	0.74
Catlin	Constant	128.3c	0.00318b	0.79
	Fluctuating	119.9c	0.00331b	0.66
Newport	Constant	150.8b	0.00482a	0.87
	Fluctuating	156.3b	0.00402a	0.64

<sup>a</sup> Different letters indicate significantly different estimates at  $P < 0.05$ , as determined by 95% confidence intervals around parameter estimates

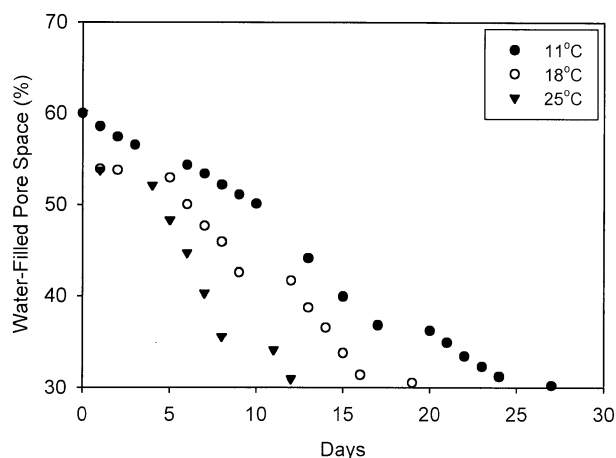
conditions. Although soil water content was reduced by half during each slow drying period (from 25% to 12.5%, on a gravimetric basis), this was clearly not sufficient to desiccate soil microorganisms, which may have led to a flush of N mineralization upon rewetting (Birch 1964; Cabrera 1993).

This amount of drying was also not sufficient to alter the nitrification rate ( $k$ ) as measured by  $NO_3^-$  accumulation. In previous research, the response of mineralization and nitrification rate to lower soil water content depended, to some extent, on soil texture. The data of Stanford and Epstein (1974) show that for sandy loam soils, reducing gravimetric soil water content by 10 percentage units (i.e. from 20% to 10%, similar to our research) had only a minimal effect on accumulation of mineral N from mineralization and nitrification. On more finely textured soils, a similar reduction in gravimetric soil water content reduced mineral N accumulation by 30–50%. Grundmann et al. (1995) also assessed the nitrification rate of a sandy loam soil, as affected by temperature (15–30°C) and soil water content. At each temperature, the rate of nitrification at relative water contents (equal to volumetric water/total porosity) of 30% and 60% were very similar, indicating that nitrification is relatively insensitive to soil water content over this range of conditions.

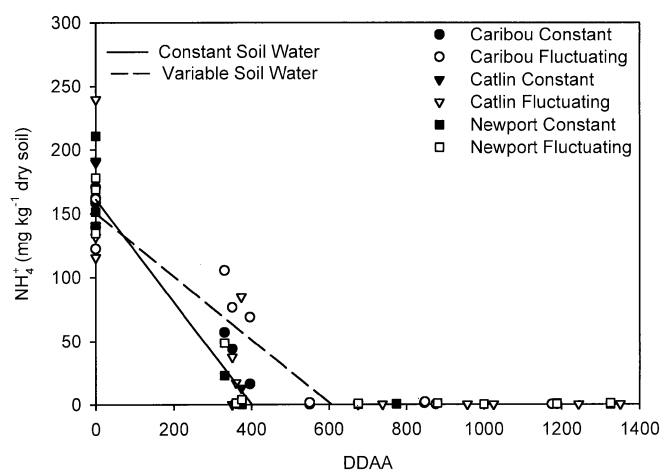
There were minimal differences between the two soil water regimes in the consumption of  $NH_4^+$  (Fig. 4), realizing that there was only a single sampling point (at 330–390 DDAA) between the time the slurry was applied and when the estimated  $NH_4^+$  concentration reached zero. The linear nature of this relationship was previously shown by Griffin and Honeycutt (2000) with a more uniform distribution of sampling points between incorporation and complete consumption of  $NH_4^+$ . At 330–390 DDAA,  $NH_4^+$  concentration in the constant and fluctuating soil water regimes was 17 and 49 mg kg $^{-1}$  dry soil, respectively (significantly different at  $P = 0.001$ ). A linear regression of  $NH_4^+$  concentration on DDAA indicates that  $NH_4^+$  concentration reached zero at approximately 400 and 600 DDAA for the constant and fluctuating soil water regimes, respectively.

#### Effects of soil type on slurry N transformation

Soil type affected the amount of  $NO_3^-$  accumulated as result of slurry application (Table 2). The amount of N nitrified was highest for the Caribou soil (198 mg  $NO_3$  kg $^{-1}$  soil, average of soil water treatments), followed by the Newport and Catlin soils (154 and 124 mg  $NO_3$  kg $^{-1}$  soil, respectively). This indicates that 62%, 77%, and 99% of total N applied was nitrified during the incubation in the Catlin, Newport, and Caribou soils, respectively, although this may not represent the ultimate extent of nitrification as the incubation proceeded to only about 1,400 DDAA. The fact that the rate of nitrification was greater in the Catlin and Newport soils lends some support to this, as it indicates that the total amount of N



**Fig. 3** Average drying rate of three soils as a function of incubation temperature; *discontinuities* represent days when incubation jars were temporarily sealed and were not weighed



**Fig. 4** The effect of constant and fluctuating soil water regimes on the consumption of ammonium-N ( $NH_4^+$ ) in three soils following application of swine slurry, as a function of degree days after application (DDAA; 0°C base). Data points are means of three observations

accumulated as  $NO_3^-$  increases more quickly in these two soils, but the total amount accumulated stabilizes at a lower level. Additionally, it appears that nitrification in the Caribou soil may not have been complete at the time the incubation was terminated, since it is still increasing slowly at approximately 1,400 DDAA (Fig. 1). It is somewhat surprising that the difference between the two Maine soils, which had similar particle size distribution and are taxonomically closely related, is larger than the difference between the Newport and Catlin soils, which are notably different in texture. The Caribou soil contains more sand (51%) than the Newport soil (42%); additionally, more of the sand is coarse ( $>0.500$  mm) in the Caribou soil (29.6% of total soil) than in the Newport soil (19.3%).

Aeration should have been similar in all three soils, which were packed to the same bulk density (1.2 Mg m $^{-3}$ ) and were maintained at the same soil water status. As discussed above, the soils dried at similar rates despite differences in texture. This suggests that it is unlikely that gaseous N loss from denitrification was significant in any case or that it affected Catlin and Newport soils to a greater extent. The clay content of all three soils was less than 20%, although the combined clay + silt ranged from 49% to 86% for

Caribou and Catlin soils, respectively. As suggested by Gordillo and Cabrera (1997b), the increase in clay + silt may limit access to decomposable substrate, especially in static incubation vessels that were not mixed during the incubation period.

In general, past research suggests that less mineralization results in greater accumulation of N and C in finer-textured soils. Bosatta and Agren (1997) presented a theoretical framework for these textural effects on decomposition. Gordillo and Cabrera (1997b) showed that the amount of N mineralized from a single poultry litter across a wide range of soils was negatively correlated with the amount of silt plus clay in the soil. Both Gordillo and Cabrera (1997b) and Sorensen and Jensen (1995) found that mineralization of manure N increased as the amount of sand increased. Franzluebbers (1999) and Giardina et al. (2001) showed that mineralization of soil organic C declined with increasing clay content in agricultural and forest soils, respectively, and suggested that this may be due to either increased immobilization by the microbial biomass or physical protection of the substrate in the soil. Thomsen et al. (2001), on the other hand, found that the addition of clay affected N mineralization, but not the addition of silt. Thomsen and Olesen (2000) evaluated manure decomposition in soil with clay contents of 11–45%, but could not draw a general conclusion that fine-textured soils differ dramatically from sandy soils.

## Conclusion

Our results show that during an aerobic incubation under either constant or fluctuating soil water, the primary factors affecting net nitrification of swine slurry N are temperature and soil type. It is possible to standardize across temperatures using DDAA with a 0°C base temperature, and net nitrification can then be predicted using a single-pool exponential model, regardless of whether soil water was constant (60% WFPS) or fluctuating (dried to 30% WFPS, then rewet to 60%). The disappearance of  $\text{NH}_4^+\text{-N}$  is also a direct (linear) function of DDAA, which is similar for all three soils but is slightly slower when soils were periodically dried and then rewet. Net nitrification was greatest for the soil with the highest sand content, and least for the soil comprised of 81% silt plus clay. Within the environmental constraints of this study, it appears that net nitrification of swine slurry can be described across soil temperature and water regimes, but should be developed separately for different soils types.

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